Va

2

National Research Council Canada
Conseil national de recherches Canada

NRC-CNRC

FLIGHT EVALUATION OF CURVED MLS PRECISION APPROACHES IN A TWIN OTTER AIRCRAFT PHASE II

by

J.B. Croll

Institute for Aerospace Research

OTTAWA
JULY 1991

AERONAUTICAL NOTE
IAR-AN-73
NRC NO. 32149

Canada

UNLIMITED
UNCLASSIFIED

INSTITUTE FOR AEROSPACE RESEARCH

SCIENTIFIC AND TECHNICAL PUBLICATIONS

AERONAUTICAL REPORTS

Aeronautical Reports (LR): Scientific and technical information pertaining to aeronautics considered important, complete, and a lasting contribution to existing knowledge.

Mechanical Engineering Reports (MS): Scientific and technical information pertaining to investigations outside aeronautics considered important, complete, and a lasting contribution to existing knowledge.

AERONAUTICAL NOTES (AN): Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

LABORATORY TECHNICAL REPORTS (LTR): Information receiving limited distribution because of preliminary data, security classification, proprietary, or other reasons.

Details on the availability of these publications may be obtained from:

Graphics Section,
National Research Council Canada,
Institute for Aerospace Research,
Bldg. M-16, Room 204,
Montreal Road,
Ottawa, Ontario
K1A 0R6

INSTITUT DE RECHERCHE AÉROSPATIALE

PUBLICATIONS SCIENTIFIQUES ET TECHNIQUES

RAPPORTS D'AÉRONAUTIQUE

Rapports d'aéronautique (LR): Informations scientifiques et techniques touchant l'aéronautique jugées importantes, complètes et durables en termes de contribution aux connaissances actuelles.

Rapports de génie mécanique (MS): Informations scientifiques et techniques sur la recherche externe à l'aéronautique jugées importantes, complètes et durables en termes de contribution aux connaissances actuelles.

CAHIERS D'AÉRONAUTIQUE (AN): Informations de moindre portée mais importantes en termes d'accroissement des connaissances.

RAPPORTS TECHNIQUES DE LABORATOIRE (LTR): Informations peu disséminées pour des raisons d'usage secret, de droit de propriété ou autres ou parce qu'elles constituent des données préliminaires.

Les publications ci-dessus peuvent être obtenues à l'adresse suivante:

Section des graphiques,
Conseil national de recherches Canada,
Institut de recherche aérospatiale,
Im. M-16, pièce 204,
Chemin de Montréal,
Ottawa (Ontario)
K1A 0R6

UNLIMITED
UNCLASSIFIED

FLIGHT EVALUATION OF CURVED MLS PRECISION APPROACHES IN A TWIN OTTER AIRCRAFT PHASE II

ÉVALUATION EN VOL D'APPROCHES PRÉCISIONS COURBES AVEC UN TWIN OTTER UTILISANT UN SYSTÈME MLS PHASE II

by/par

J.B. Croll

Institute for Aerospace Research

OTTAWA
JULY 1991

AERONAUTICAL NOTE
IAR-AN-73
NRC NO. 32149

S.R.M. Sinclair, Head/Chef
Flight Research Laboratory/
Laboratoire de recherches en vol

G.F. Marsters
Director General
Le directeur général

SUMMARY

Phase II flight testing of curved, segmented approaches using a Microwave Landing System (MLS) was conducted on a Twin Otter aircraft belonging to the Canadian National Research Council's Institute for Aerospace Research (IAR). Precision guidance algorithms were developed for approaches with track angle changes exceeding 180°. Software development flights focussed on validating these algorithms and enhancing the existing electromechanical flight director to ease the pilot workload in tracking the curved segments. A limited number of pilot evaluations confirmed that with an enhanced lateral flight director, these approaches could be flown satisfactorily regardless of the magnitude of the track angle changes. Observations were made on approach design and wind effects on curved segment tracking.

RÉSUMÉ

Un Twin Otter de l'Institute de recherche aérospatiale (IRA) du Conseil national de recherches a été utilisé pour la réalisation de la deuxième phase de l'évaluation en vol d'approches courbes et segmentées à l'aide d'un système d'atterissage à hyperfréquences (MLS). On a établi des algorithmes de guidage de précision pour des approches avec des écarts d'angle de route dépassant 180°. Les vols servant à l'élaboration de logiciel visaient principalement la validation de ces algorithmes et l'amélioration du directeur de vol électromécanique existant en vue de simplifier la charge de travail des pilotes lorsqu'ils suivent des segments courbes. Un nombre limité d'évaluations par les pilotes a confirmé qu'avec un directeur de vol latéral amélioré, ces approches pourraient être effectuées de façon satisfaisante indépendamment de l'amplitude des écarts d'angle de route. Des observations ont été faites relativement aux configurations d'approche et aux effets du vent sur le maintien de la route sur des segments courbes.

TABLE OF CONTENTS

LIST OF FIGURES

GLOSSARY OF TERMS

ADI	Attitude Director Indicator
APPDEF	Approach Definition software program
APPMON	Approach Monitor software program
ARINC	Aeronautical Radio Incorporated
ATD	Along Track Distance from the aircraft to touchdown
ATS	Air Traffic Services
CTD	Cross Track Deviation
DEC	Digital Equipment Canada
DME/P	Precision Distance measuring Equipment
FDC	Flight Director Computer
FDR	Flight Director Roll signal
HSI	Horizontal Situation Indicator
IAR	Institute for Aerospace Research
LSI	Large Scale Integration
MLS	Microwave Landing System
RTCA	Radio Technical Commission for Aeronautics
STOL	Short Takeoff and Landing
T/D	Touchdown
VTD	Vertical Track Deviation

LIST OF SYMBOLS

ATD	along track distance from the aircraft to the touchdown point
CTD	cross track deviation
CTD_{BIAS}	biased CTD signal applied to the FDC on curved segments
d_i	length of the (i) straight segment or curved segment arc
D	distance between the MLS azimuth transmitter and the touchdown point
g	acceleration due to gravity
G_1, G_2, G_3	gains applied to the FDR signal
G_{AZ}	azimuth scaling factor applied to the FDR signal
I_i	direction of turn parameter for curved segment (i)
r_i	radius of turn of the (i) curved segment arc
VTD	vertical track deviation
V_G	aircraft groundspeed
x_a, y_a, z_a	aircraft x,y,z coordinates
xc_i, yc_i	xy coordinates of the center of curved segment (i)
x_i, y_i, z_i	coordinates of straight or curved waypoint (i)
y_0	lateral offset of the MLS elevation transmitter from the runway centreline
δ	MLS elevation angle
λ_i	glideslope of the (i) segment
νA_i	angle turned through by the aircraft on curved segment (i)
νc_i	track angle change of the (i) curved segment
ν_i	track angle of the (i) straight segment with respect to runway C/L
ρ	line of sight distance from the aircraft to the MLS azimuth site
ϕ	aircraft bank angle
ϕ_0	curved segment bank angle required for zero CTD
ψ	MLS front azimuth angle

FLIGHT EVALUATION OF CURVED MLS PRECISION APPROACHES IN A TWIN OTTER AIRCRAFT - PHASE II

1.0 INTRODUCTION

1.1 Background

Early in 1989, an agreement was made between the Transport Canada MLS Project Office and the Flight Research Laboratory of the Institute for Aerospace Research (IAR) to conduct an operational research and development program on the Microwave Landing System (MLS) installed at the Ottawa International Airport. The purpose of this program is to develop curved, segmented approaches making use of the wide angle MLS signal coverage available, and to demonstrate the benefits of these approaches to Canadian Air Traffic Services (ATS) and Air Carrier personnel. Simulations and flight tests of these approaches have recently been accomplished in other countries, in particular The Netherlands (Reference 1) and the United States (Reference 2). This program is meant to complement ongoing international research and set the stage for collaboration.

The overall Transport Canada/IAR MLS development program will be accomplished on two different types of aircraft, the Twin Otter and the Falcon 20. The Twin Otter testing was designed to encompass initial algorithm development as well as initial pilot evaluations of curved, segmented approaches. The results of this work, including flight director enhancements and final software configuration, will be transferred to the Falcon 20 for further development and demonstration to the user community.

To date, two phases of testing have been completed on the IAR Twin Otter aircraft. The first phase included software development and flight evaluation of curved, segmented approaches with track angle changes up to 90 degrees. It was flown during the winter of 1989/1990, and reported on in Reference 3. During this phase it was found that lateral track deviations and pilot workload increased as a function of the magnitude of the approach track angle change, but this was largely due to lateral flight director limitations which forced the pilots to fly the approaches using mainly raw data.

1.2 Scope

This paper covers the second phase of testing carried out on the IAR Twin Otter during the winter of 1990/91. The objectives of this phase were to rewrite the algorithms for curved, segmented approaches incorporating track angle changes beyond 180 degrees, to validate these algorithms in flight, and to assess pilot workload and tracking accuracies for selected approaches using a properly functioning flight director.

It was not the intent of this phase to adjust the gains of the lateral flight director itself, but rather to make minor changes to the computed inputs to the flight director in order to permit curved segment tracking.

2.0 EQUIPMENT DESCRIPTION

The MLS installation at the Ottawa International Airport consists of an approach azimuth transmitter located 933 metres from the departure end of runway 32, on the extended runway centreline, with a horizontal beam coverage of ± 40° (Figure 1). The MLS glideslope transmitter is located abeam the aircraft touchdown point on runway 32 (315 metres from the runway threshold) and is offset to the left of the runway by 113 metres. The MLS is selectable on channel 522 (azimuth frequency of 5037.6 MHz).

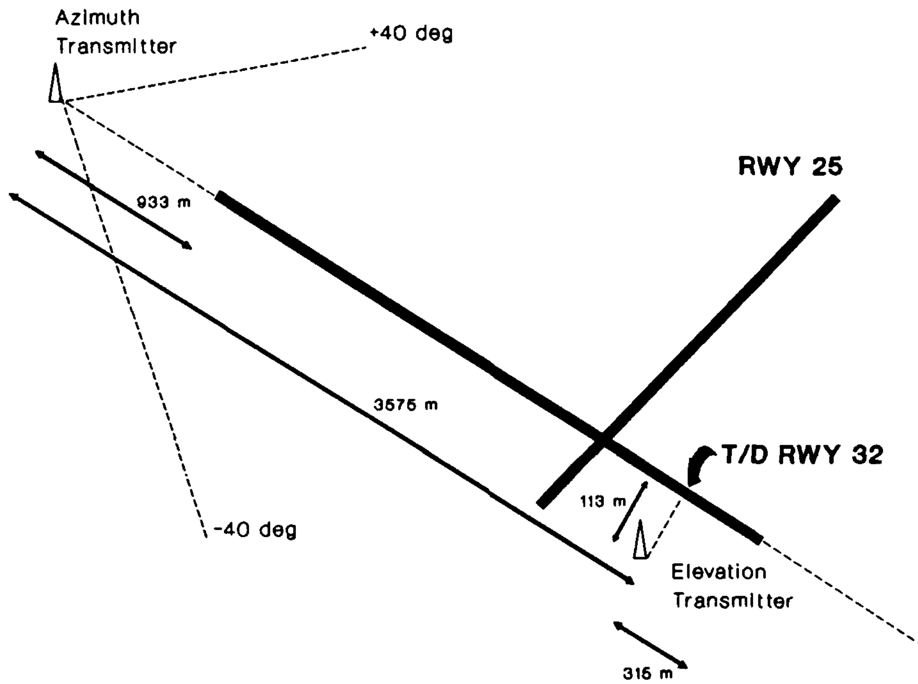

Figure 1
MLS Installation at Ottawa International Airport

The IAR Twin Otter, registration C-FPOK, is a Short Takeoff and Landing (STOL) transport aircraft built by deHavilland of Canada and extensively modified by the IAR. Onboard computing capability is available in a Digital Equipment Canada (DEC) LSI-11/73 computer which provides computations of several aircraft parameters, including angles, rates, and velocities. Full interaction with the main LSI-11/73 processor is provided by a console mounted keyboard and plasma display. Sensor outputs and computed parameters are recorded on a streamer tape data acquisition system; a total of 128 parameters written in 16-bit words can be recorded at rates up to 16 samples per second. The system provided real-time processing of all MLS data. Diskettes containing the MLS approach constants and the executable program were loaded into a dual floppy disk unit in the aircraft cabin area.

The Twin Otter was equipped with a Bendix MLS-20A Microwave Landing System. The digital angular output data of the on-board MLS receiver (azimuth and glideslope

angles) were transmitted in the ARINC 429 format to the LSI-11/73. Since a Precision Distance Measuring Equipment (DME/P) receiver was not available, a special Microwave Transponder (Del Norte 540) was used for distance information. A remote transponder co-located with the MLS azimuth transmitter was interrogated by the Del Norte 540 Master Transponder onboard the aircraft. This provided a distance measurement which was at least as accurate as that of a DME/P, and in conjunction with the MLS azimuth and glideslope angles, was used to calculate the current aircraft position.

In evaluating the curved MLS approaches, a Collins FD-109H Integrated Flight System was used by the pilots. This system consisted of an electro-mechanical Attitude Director Indicator (ADI) and Horizontal Situation Indicator (HSI), and was modified to accept computed signals from the LSI-11/73. These signals included cross track deviation (CTD) and vertical track deviation (VTD) as well as course and bearing information. The data flow to the pilot's Integrated Flight System is shown in Figure 2. The digital CTD and VTD signals were converted to analogue and sent to the appropriate symbols on both the HSI and ADI. The VTD signal was also sent to the Flight Director Computer (FDC) for processing into pitch command bar indications, employing the standard gains of the Collins system. The CTD signal was augmented by a bank angle bias signal for the curved segments, becoming what was termed the Flight Director Roll (FDR) signal prior to being sent to the FDC for processing into roll bar commands. In this way, the appropriate bank angle command was provided for curved segments (based on the programmed radius of turn), as well as straight segments.

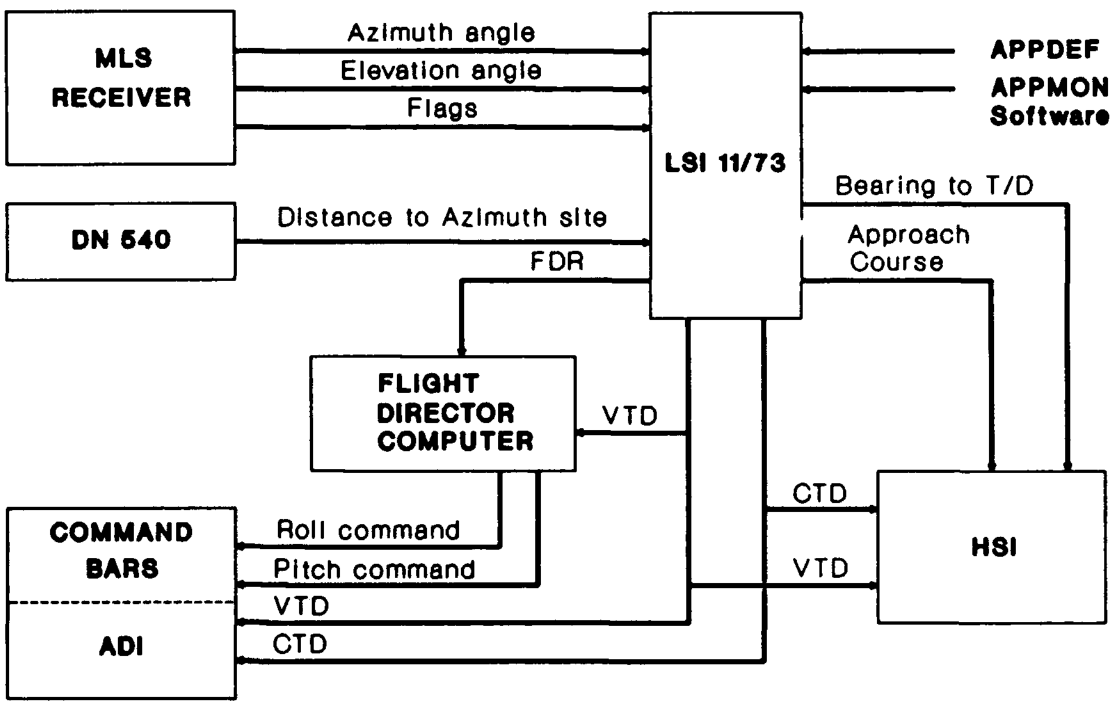

Figure 2
Data Flow to the Pilot's Integrated Flight System

The function of the HSI heading marker during the approaches was changed to indicate the bearing to the aircraft touchdown point on the runway. This modification was meant to provide the pilot with a sense of orientation for approaches highly offset from the runway centreline. The HSI course arrow and window presentations were also modified to automatically display the required approach course for both straight and curved segments. This kept the approach course updated (course arrow approximately vertical) while flying the curved segments.

3.0 GUIDANCE COMPUTATIONS

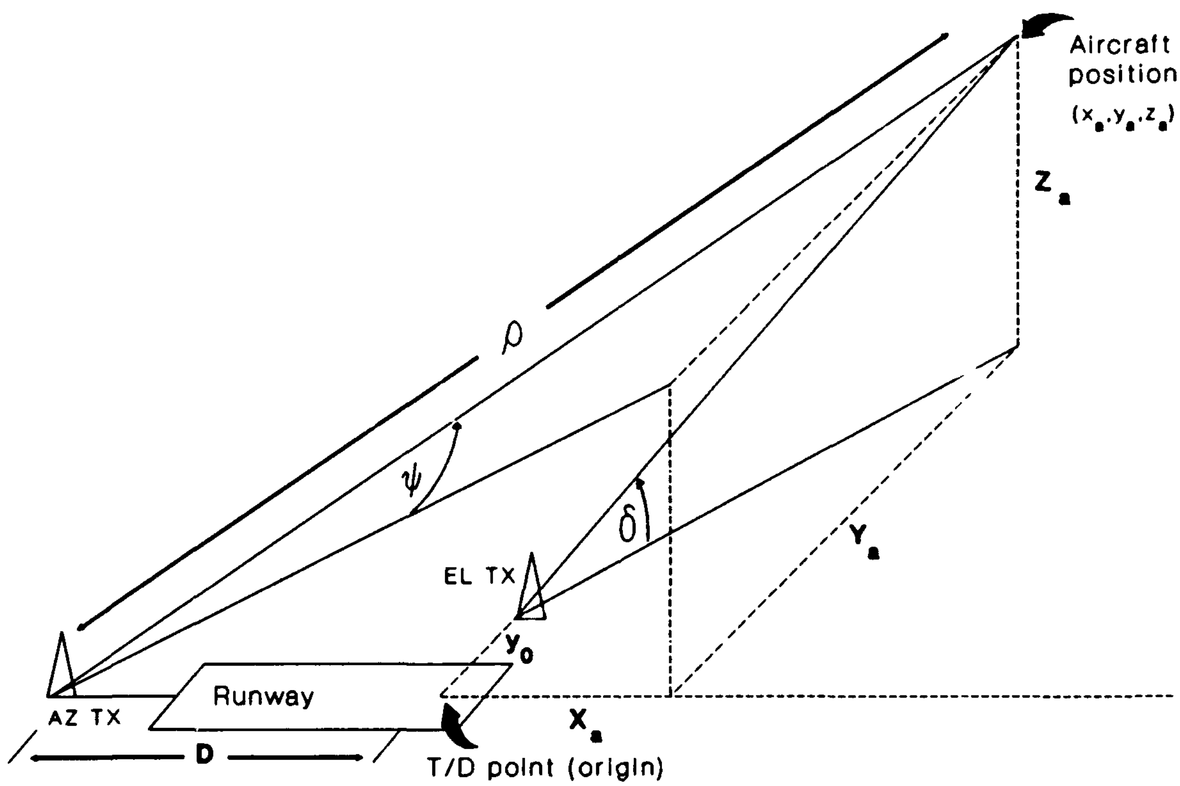

Figure 3
MLS Parameter Symbology

3.1 Aircraft Position

Using the symbology shown in Figure 3, the aircraft position coordinates x_a, y_a, and z_a (referenced to the touchdown point as the origin) are calculated as a function of the MLS parameters and slant range distance using the following equations:

$$x_a = -D\cos^2\delta + \sqrt{D^2\sin^4\delta - \sin^2\delta\,(y_0^2 - 2y_0\rho\sin\psi + \rho^2 + D^2) + \rho^2\cos^2\psi} \qquad (1)$$

$$y_a = \rho \sin\psi \qquad (2) \qquad\qquad z_a = \tan\delta \sqrt{x_a^2 + (y_a - y_0)^2} \qquad (3)$$

where ψ is the MLS azimuth angle ($\psi = 0$ in the xz plane), δ is the MLS elevation angle ($\delta = 0$ in the xy plane), ρ is the line of sight distance to the MLS azimuth transmitter, D is the distance between the MLS azimuth transmitter and the touchdown point, and y_0 is the lateral offset of the elevation transmitter from the runway centreline. For the installation at Ottawa, D = 3575m and y_0 = -113m.

The assumptions made for the above equations are that the azimuth transmitter, elevation transmitter, and runway touchdown point are all in the same plane, and that the aircraft remains on the approach side of the azimuth transmitter.

3.2 Approach Variables and Deviations

By definition, the general approach track (Figure 4) consists of alternating straight and curved segments, each segment (i) starting at its own waypoint defined by coordinates (x_i, y_i, z_i). Segments are numbered beginning with the final approach straight segment (number 1), and proceeding backwards along the approach. The touchdown point is referred to as waypoint 0 ($x_0 = y_0 = z_0 = 0$).

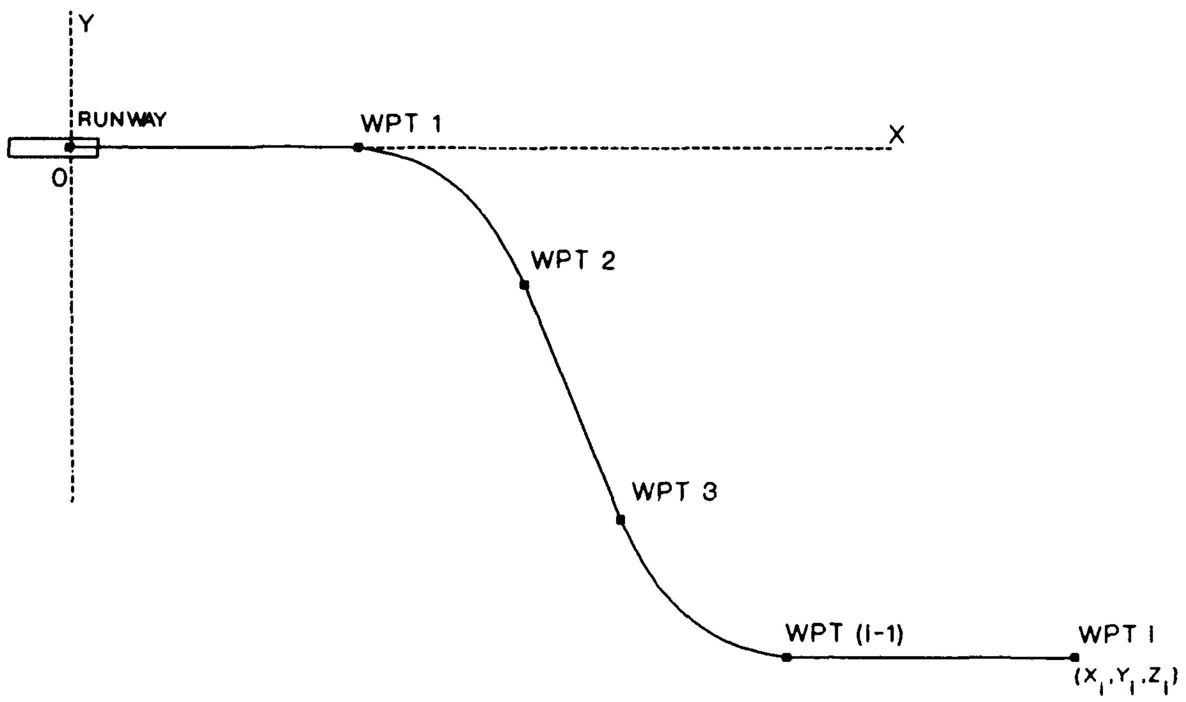

Figure 4
General Approach Definition

Various segment parameters are defined or calculated for both straight and curved segments. Distance d_i represents the length of straight segment (i) or the arc length of curved segment (i); λ_i is the glideslope of the (i)th segment; ν_i is the track angle of the (i)th straight segment referenced to the runway centreline; and νc_i is the track angle change of the (i)th curved segment. Additional parameters defined for curved segment (i) are the radius of turn r_i, the xy coordinates of the circle center xc_i and yc_i, and the direction of turn parameter I_i (+1 for a right turn, and -1 for a left turn).

The lateral difference between the position of the aircraft and the approach track, or CTD, is calculated by comparing the current aircraft position coordinates (x_a, y_a, z_a), as determined in equations (1), (2), and (3), to the appropriate parameters of the segment being flown. For straight segment (i), CTD is calculated as follows:

$$CTD = (x_a - x_{i-1}) \sin \nu_i + (y_a - y_{i-1}) \cos \nu_i \tag{4}$$

and for curved segment (i):

$$CTD = I_i \left[r_i - \sqrt{(x_a - xc_i)^2 + (y_a - yc_i)^2} \right] \tag{5}$$

where subscript (i-1) refers to the subsequent segment data. The difference between the position of the aircraft and the approach track in the vertical plane, or VTD, is calculated as follows for either straight or circular segment (i):

$$VTD = z_a - \left(z_{i-1} + \sqrt{(x_a - x_{i-1})^2 + (y_a - y_{i-1})^2 - CTD^2} \tan \lambda_i \right) \tag{6}$$

The distance remaining between the aircraft and the touchdown point along the remaining approach segments is defined as the along track distance (ATD). This parameter must be continuously computed in order to determine the appropriate segment for CTD and VTD calculations. For straight segment (i), ATD is calculated as follows:

$$ATD = \sum_{j=1}^{i-1} d_j \pm \sqrt{(x_a - x_{i-1})^2 + (y_a - y_{i-1})^2 - CTD^2} \tag{7}$$

For curved segment (i), ATD is given by:

$$\begin{gathered} ATD = \sum_{j=1}^{i-1} d_j + (d_i - r_i |\nu A_i| \cdot \pi / 180) \ ; \\ \nu A_i = -\nu_{i+1} + \arctan \frac{(x_a - xc_i)}{(y_a - yc_i)} \end{gathered} \tag{8}$$

where νA_i is the angle (along track direction change) turned through by the aircraft on curved segment (i), and subscript (i+1) refers to previous straight segment data. Segment switching is accomplished at or abeam each waypoint by comparing the aircraft ATD to the segment parameters defining the approach.

4.0 SOFTWARE DESCRIPTION

The airborne computer program written for the MLS project was an extension of the earlier Twin Otter program used for atmospheric research. The MLS approach monitor (APPMON) program, the source of the computations described above, was written in the Fortran IV language for ease in handling the algebraic functions. An off-line program labelled APPDEF (approach definition) was also created in Fortran IV to generate the dataset containing the various approach parameters.

The APPMON program monitored the progress of the aircraft along a pre-selected approach path and computed the deviations and other approach variables sent to the pilot's Integrated Flight System as shown in Figure 2. The subroutine was entered by calling up the two digit number of the desired approach on the keyboard. This activated a search for the appropriate dataset on the directory of a diskette which had been generated using the APPDEF program and loaded into one of the aircraft disk drives. A successful read resulted in transfer of the dataset to the main memory, and transfer of control to the computational portion of the APPMON subroutine. Computations continued throughout the approach until the aircraft passed the touchdown point, or the co-pilot cancelled the approach on the keyboard.

5.0 APPROACHES FLOWN

The approaches flown during Phase II of the Twin Otter program are depicted in Figures 5 and 6. Figure 5 shows three approaches with three segments each, offset to the left of the runway centreline with track angle changes of 90, 135, and 180 degrees. These approaches were chosen as operationally beneficial in allowing an aircraft to arrive from points west of Ottawa and fly a curved precision approach to runway 32 without the need for radar vectoring to a long final straight in approach. The final segment for the 90 degree curved approach was 2.0 nautical miles (nm) in length, while the final segments for the 135 and 180 degree approaches were 3.0 nm long. This distance was chosen not because of minimum final segment length criteria, but simply to keep the approach intercept points inside the MLS azimuth coverage area ($\pm 40^\circ$) shown in Figure 5. All of the curved segments had a 1.0 nm radius of turn, designed so that the Twin Otter approach speed of about 100 knots would result in a bank angle of less than 10° (no wind). Since the flight evaluations concentrated primarily on variations in the horizontal geometry of the approach, the glideslopes were set at 3.0°.

Figure 6 shows a seven segment approach with a total track angle change of 225 degrees. This approach was designed primarily to demonstrate the versatility of the APPMON software and to assess the effect of flying relatively short curved segments as opposed to a long continuous turn. The final segment length was 3.0 nm, again required to maintain the initial approach segments within the azimuth coverage area.

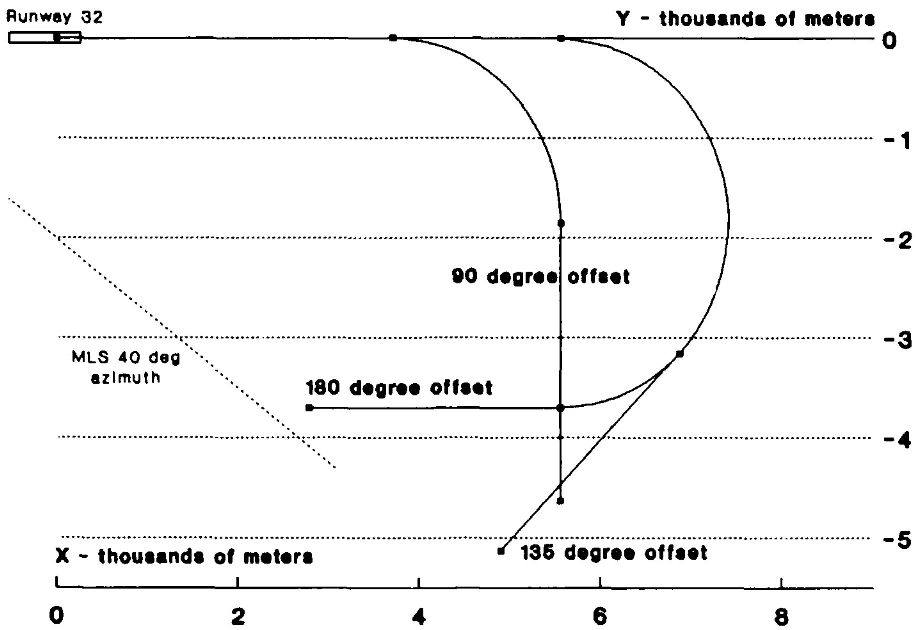

Figure 5
Three Segment Offset Approaches

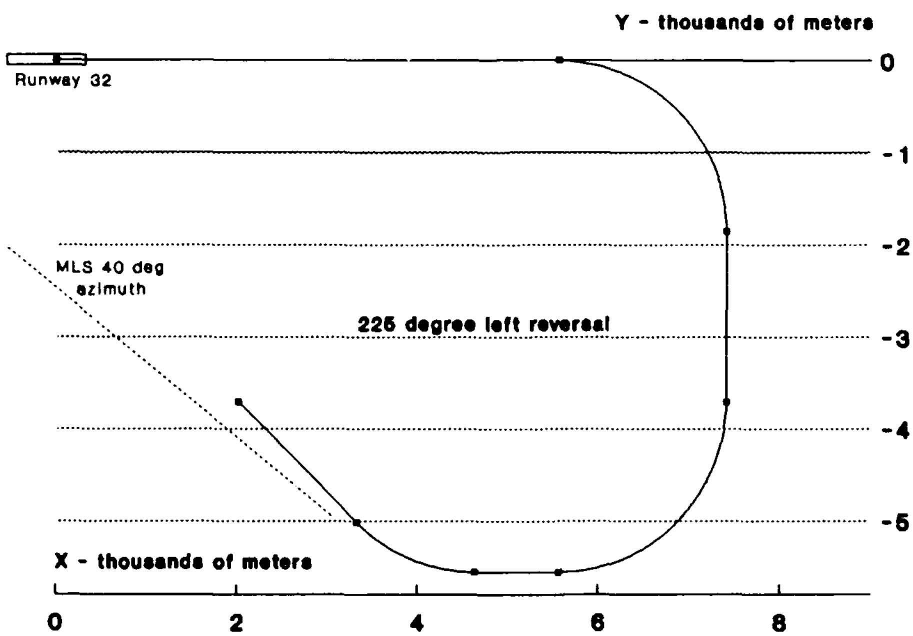

Figure 6
Seven Segment Approach

6.0 SOFTWARE DEVELOPMENT

In order to ensure proper implementation of the various equations used to calculate the real time values of CTD, VTD, and ATD (described in section 3.0), several changes had to be made to the APPMON software previously used for Phase I. Major changes included the following:

a. redefinition of segment switching algorithms;
b. changes to both azimuth and elevation deviation sensitivities;
c. a change to the lateral flight director gain; and
d. addition of turn and rollout anticipation cuing blended in to the lateral flight director.

These changes were made over a two month period during November and December 1990, and required ten flights for validation during this period.

6.1 Segment Switching

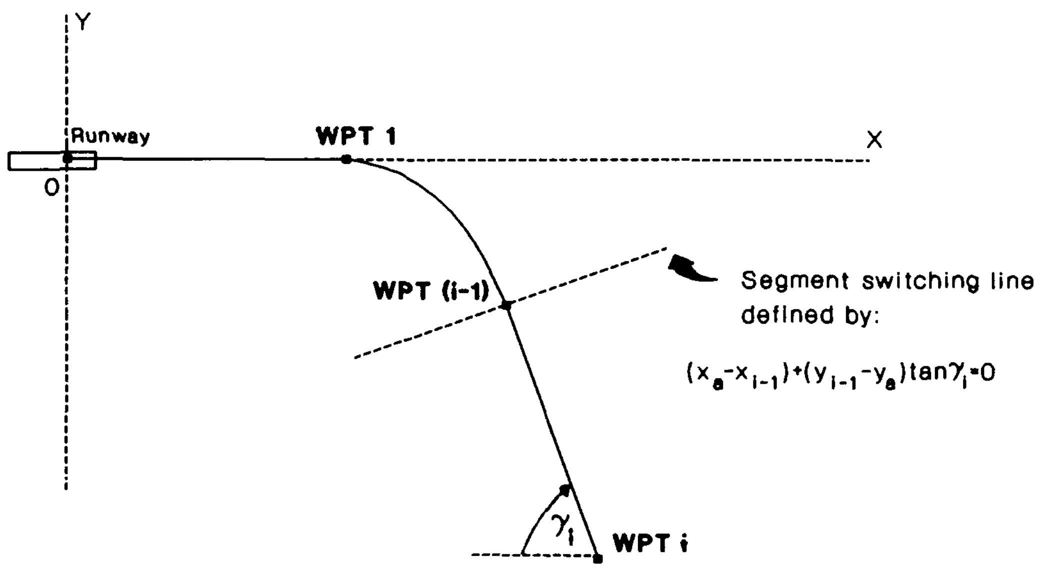

Figure 7
Segment Switching Abeam Waypoints

Switching from straight segment (i) to curved segment (i-1) was enabled when the aircraft passed abeam the waypoint (Figure 7) defining the start of the curved segment. The following expression defined a sign (+1 or -1) on either side of the segment switching line:

$$sign = \frac{(x_a - x_{i-1}) + (y_{i-1} - y_a)\tan\nu_i}{|(x_a - x_{i-1}) + (y_{i-1} - y_a)\tan\nu_i|} \qquad (9)$$

The sign of this unitary quantity changed from positive to negative when passing abeam the end of a straight segment (i) where the track angle ν_i was in the range -90°< ν_i< 90°. The result of equation (9) determined the sign of the square root portion of equation (7). With a change from positive to negative, the aircraft distance to go to touchdown (ATD) became less than the distance to go from the (i-1) waypoint. The actual switch to the (i-1) curved segment was made on the basis of this decrease in ATD. For 90°< $\nu_i \leq$ 180° or -180° $\leq \nu_i$< -90°, equation (9) for "sign" was multiplied by -1 and implemented in a similar manner. For special cases ν_i= 90° or ν_i= -90°, the following equations were used:

$$
\begin{aligned}
sign &= \frac{(y_{i-1}-y_a)}{|y_{i-1}-y_a|} \quad for\ \nu_i = 90° \ ; \\
sign &= \frac{(y_a-y_{i-1})}{|y_{i-1}-y_a|} \quad for\ \nu_i = -90°
\end{aligned}
\tag{10}
$$

Switching from curved segments (i) to straight segments (i-1) was based on the calculation of the aircraft track angle change νA_i and distance ATD from equation (8). Corrections were made in the software to account for the orientation of the previous straight segment track angle ν_{i+1}, the direction of turn on the curved segment, and the angular discontinuity at ±180° as a result of the arctangent function of equation (8).

6.2 Deviation Sensitivities

Azimuth and elevation deviation sensitivities were changed from those used during Phase I to values identical to those defined by the RTCA (Radio Technical Commission for Aeronautics) document DO-198 for Level III procedures, as detailed in Reference 4. The full scale deflection limits for the CTD display on the aircraft HSI (shown in Figure 8) were set as follows:

a. ±350 feet from touchdown point to ATD = 6080 feet (1 nm);
b. splay angle of ±3° for 6080 feet < ATD < 28,023 feet (4.6 nm); and
c. ±1500 feet for ATD ≥ 28,023 feet.

The full scale deflection limits for the VTD display on the aircraft HSI and ADI (also shown in Figure 8) were set as follows:

a. ±50 feet from touchdown to ATD = 3816 feet (.6 nm);
b. splay angle of ±0.75° for 3816 feet < ATD < 19,094 feet (3.1 nm); and
c. ±250 feet for ATD ≥ 19,094 feet.

The resolution of the CTD data met the minimum specification of Reference 4, with a setting of ±1/256th of full scale HSI deflection updated at 8 Hz. The VTD resolution was double the Reference 4 specification, with a setting of ±1/512th of full scale ADI/HSI deflection updated at 8 Hz.

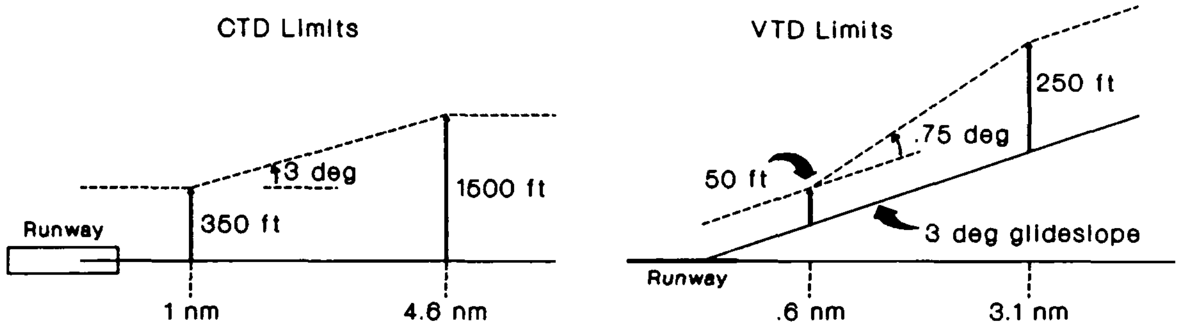

Figure 8
CTD and VTD Full Scale Deflection Limits

6.3 Lateral Flight Director

During Phase I testing the FD-109 lateral flight director was not used to advantage due to an internal problem with the flight director computer which could not be addressed during the actual test program. Following this program, the FDC was sent back to the manufacturer for overhaul. Its performance during the Phase II development flights was good, but some changes were made to the lateral deviation input signal to the flight director to enhance the pilot's ability to fly the curved segments. These changes included gain adjustments and turn and rollout anticipation.

The lateral deviation input signal (FDR as discussed in section 2.0) to the flight director was the sum of contributions from both CTD and CTD_{BIAS} according to the following equation:

$$FDR = (G_1 \times CTD \times G_{AZ}) + (G_2 \times CTD_{BIAS}) \tag{11}$$

where G_1 and G_2 are gains, and G_{AZ} is the azimuth scaling factor required to achieve the sensitivities described in section 6.2.

CTD_{BIAS} was an additional deviation input required to command the correct bank angle (ϕ_0) on a curved segment for zero CTD. CTD_{BIAS} was programmed as a direct function of ϕ_0, and ϕ_0 was calculated from the existing groundspeed (V_G) and other curved segment parameters as follows:

$$CTD_{BIAS} = -G_3 \times \Phi_0 \;; \qquad \Phi_0 = I_i \times \arctan\frac{V_G^2}{g\, r_i} \tag{12}$$

where G_3 is a gain, and "g" is the acceleration due to gravity.

During the Phase II development flights, the gain G_1 of equation (11) was increased to provide tighter approach tracking as a function of CTD. The intent was to reduce the magnitude of approach track deviations without significantly affecting pilot workload, while retaining sufficient flight director authority to command the required curved segment bank angle ϕ_0. Gains G_2 and G_3 were not altered, having been optimized during Phase I.

Turn and rollout anticipation cues were provided on the lateral flight director by blending in the bank angle as shown in Figure 9. During the last three seconds of a straight segment (i), equivalent to a distance of $3V_G$, the zero CTD commanded bank angle was introduced in a linear fashion, reaching a value of ϕ_0 at the beginning of the curved segment (i-1). During the curved segment, the calculated value of ϕ_0 (proportional to changes in groundspeed) was displayed on the flight director roll bars. During the last three seconds of the curved segment, the zero CTD commanded bank angle decreased to zero for the beginning of the next straight segment.

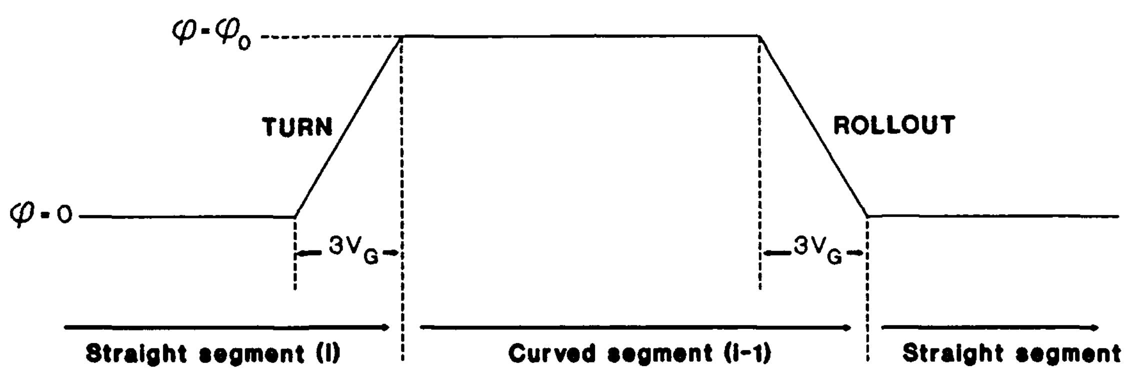

Figure 9
Turn and Rollout Anticipation Mechanization

7.0 PILOT EVALUATION FLIGHTS

Following the software development flights, three test pilots evaluated several approaches each during the month of January 1991. The purpose of these flights was to assess the workload and tracking accuracy encountered while flying various curved approaches, including those shown in Figures 5 and 6. All the pilots had some experience in flying the curved, segmented approaches of Phase I. The author acted as the safety pilot in the co-pilot's seat for the evaluation flights. All approaches were flown to category I minimums on instruments only (visual weather conditions) using full flight director assistance. A short questionnaire was completed by the evaluation pilot after the execution of each approach. Time histories of the approach parameters were recorded on the Twin Otter streamer tape.

7.1 Approach Segment Tracking

Figure 10 shows the tracking accuracy which could be obtained in a relatively light wind situation. During this 180° offset approach, the average wind was from 260° magnetic at 12 knots. This produced a maximum left crosswind component at a point about two thirds of the way through the curved segment. A slight deviation to the right of track resulted, but reached a maximum of only 200 feet and was easily compensated for within the authority of the lateral flight director.

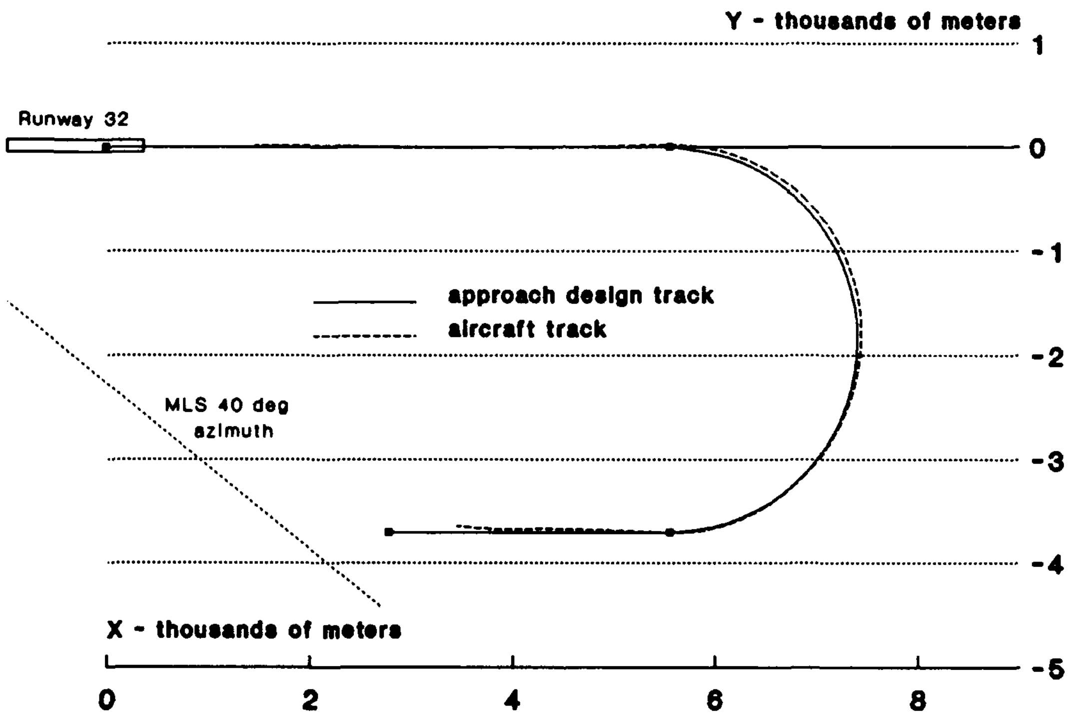

Figure 10
180° Offset Approach, Flight 10

For approaches made in light wind conditions, the behaviour of the flight director was excellent on both straight and curved segments. Turn anticipation cuing worked very well in helping the pilot to establish the correct bank angle at the beginning of the curved segment. Rollout anticipation cuing decreased the commanded bank angle but tended to overshoot briefly in the opposite direction, resulting in some overcontrolling of the aircraft if followed too closely. This was a minor annoyance to the pilots, and should be corrected prior to the next phase of testing by incorporating a gentler washout mechanization for the rollout cues.

Several approaches were flown in conditions of moderate to strong winds. Figure 11 depicts another 180° offset approach flown in wind speeds of 25 to 30 knots from a direction

of 250° magnetic. The aircraft track diverged slightly to the outside of the approach design track during the first third of the 180° turn, but the lateral deviation input signal FDR as defined in equation (11) remained within the authority of the flight director (a maximum of about 15° bank angle on a precision approach). At the point of maximum tailwind component, a bank angle ϕ_0 of over 12° was required due to the increased groundspeed V_G. The combination of ϕ_0 plus the additional left bank required to correct back to the approach track slightly exceeded the lateral flight director authority during the second third of the turn. This resulted in a further deviation from the approach track to a maximum CTD of about 530 feet. As the groundspeed decreased during the second half of the turn, the corresponding decrease in ϕ_0 allowed additional flight director authority to correct back to the approach track.

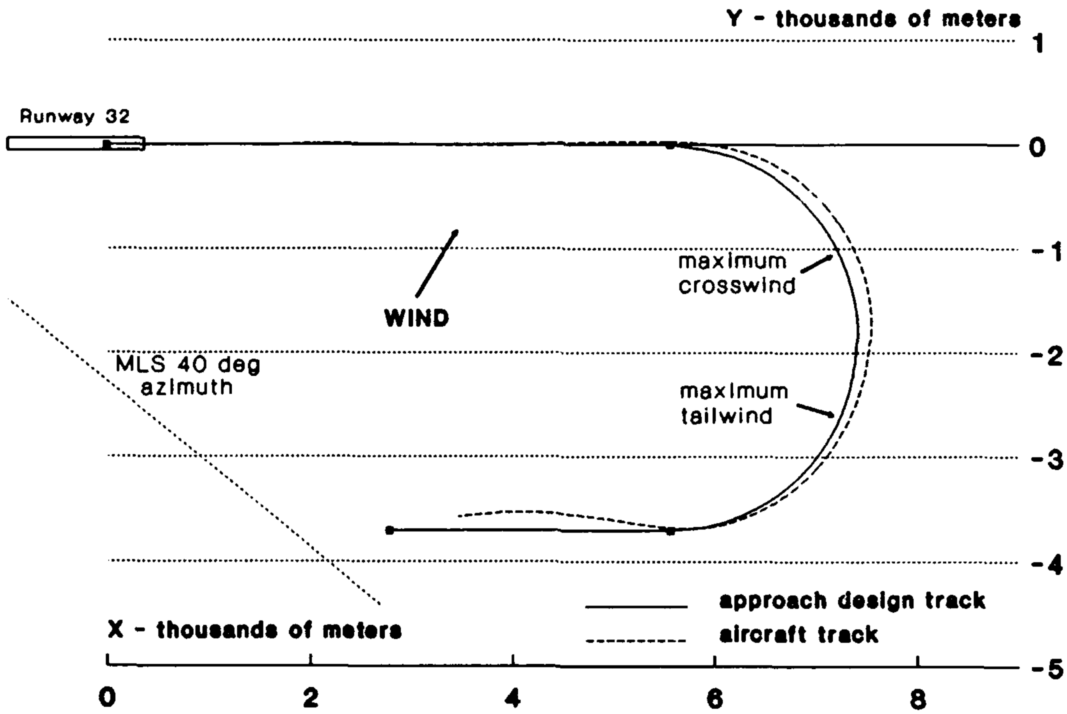

Figure 11
180° Offset Approach, Flight 12

The pilot followed the flight director precisely during the above approach without making corrections using raw data. This was the easiest way to fly this type of approach, and resulted in CTD's well within approach tolerances even with strong winds; a CTD of 530 feet was equivalent to about 40 percent of HSI full scale deflection to the right at an ATD of about 4.25 nm. Although satisfactory to the pilots, the performance of the lateral flight director could be improved by any of the following four methods:

a. adjusting the gains G_1, G_2, and G_3 applied to the computed parameters of equations (11) and (12);

b. adding an integral wind correction term to the flight director;
c. increasing the bank angle authority of the flight director to beyond the customary 15° limit for a precision approach; or
d. widening the design radius of turn for the curved segments.

Option a. above represents the simplest method of improving curved segment tracking capability, and would require additional flight tests to optimize the lateral flight director. Options b. and c. would require changes to the flight director itself, rather than just the lateral deviation input signal (FDR). Option d. would have the disadvantage of lengthening the final straight segment to keep the approach track within the $\pm 40°$ azimuth coverage area. The point to be made here is that the relative changes in the wind direction experienced during a curved approach need to be taken into consideration in the design of a flight director adequate for the tracking task.

Curved segment tracking performance improved during approaches where a large track angle change (above 180°) was divided into shorter curved segments separated by straight segments. Figure 12 shows a 225° seven segment approach flown on the same flight as the approach shown in Figure 11. Full lateral flight director authority was available during the intermediate straight segments to correct any deviations developed during the curved segments. Although the approach involved several turns, the maximum CTD was only 180 feet.

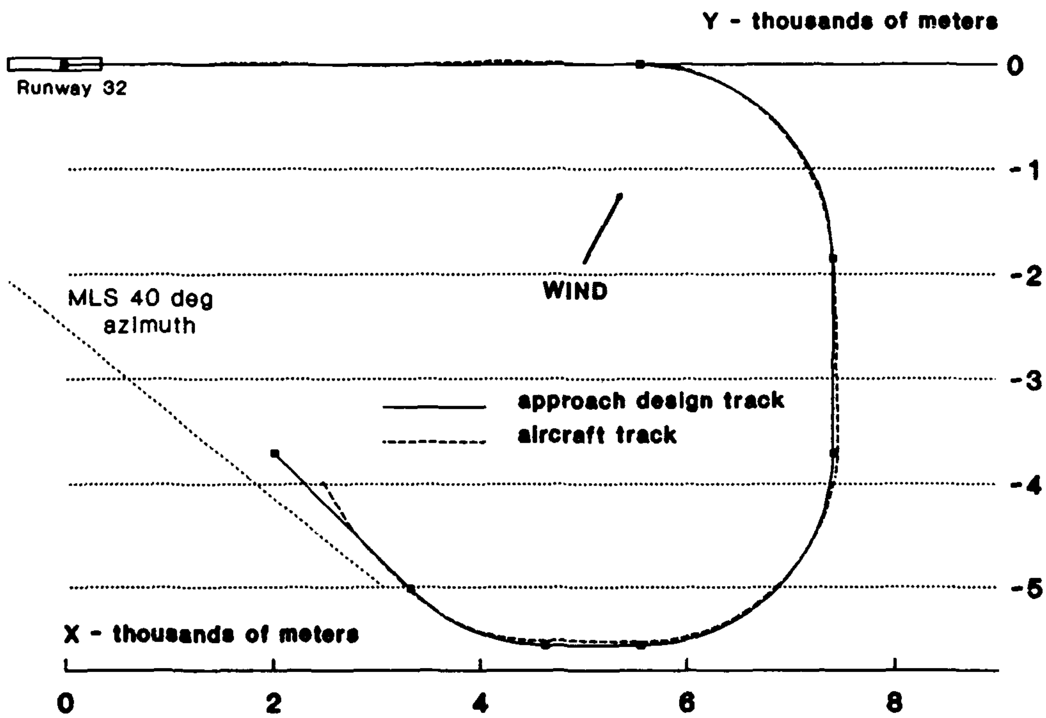

Figure 12
225° Seven Segment Approach, Flight 12

As evidenced by the approach tracking histories in Figures 10, 11 and 12, the rollout on the final straight segment during the evaluation flights was always very close to the approach track, and did not show much dependence on the track angle change of the previous curved segment. For the Twin Otter aircraft, the minimum length of the final segment could be much less than the 3.0 nm for the approaches shown. This length would be dependent on the approach geometry, the MLS azimuth coverage area, and the minimum desired maneuvring altitude for the turn onto final. From the results of this evaluation, tracking performance would not be a factor in determining the minimum length of the final segment.

The flight director pitch axis worked well throughout the evaluations, and glideslope tracking was well within acceptable limits for all approaches. The glideslope intercept point occurred on a straight segment for most approaches, but was also programmed to take place on a curved segment for some approaches, including the 180° offsets shown in Figures 10 and 11. The pilots did not state a preference for either method, as long as lateral segment tracking was well established prior to glideslope intercept. This is contrary to the findings of Reference 1, which discouraged glideslope intercepts on curved segments. The difference in this evaluation, however, was the low pilot workload required for lateral tracking of curved segments with a good flight director, and the additional time available to recognize and intercept the glideslope.

7.2 Approach Track Deviations and Pilot Workload

The maximum CTD's experienced during each approach were determined from the recorded parameters and averaged for similar approaches flown by the different pilots. These data were plotted along with the corresponding average pilot ratings as a function of the approach track angle changes. The results are shown in Figure 13.

Despite the limited data obtained from only three pilots, the workload ratings were very consistent. Figure 13 shows the average workload to fall within the "satisfactory" category for all approaches flown from 90° offset to 225° seven segment approaches. With a fully functional lateral flight director, modified as described in section 6.3, the magnitude of the track angle change did not influence the pilot's ability to fly the approach. The pilot simply flew the aircraft in accordance with the commands generated by the flight director while monitoring the raw deviation data on the aircraft HSI. This result was markedly different from the results of Phase I testing, where the lack of a properly functioning flight director precluded satisfactory lateral tracking of curved segments beyond about 60° of track angle change.

The maximum CTD's, averaged over the evaluation flights, are also shown in Figure 13. The largest deviations of about 500 feet occurred during the 180° left offset approaches, and were mainly due to the wind effects discussed in section 7.1. The lower average CTD's associated with the seven segment approaches are also consistent with the discussions in section 7.1.

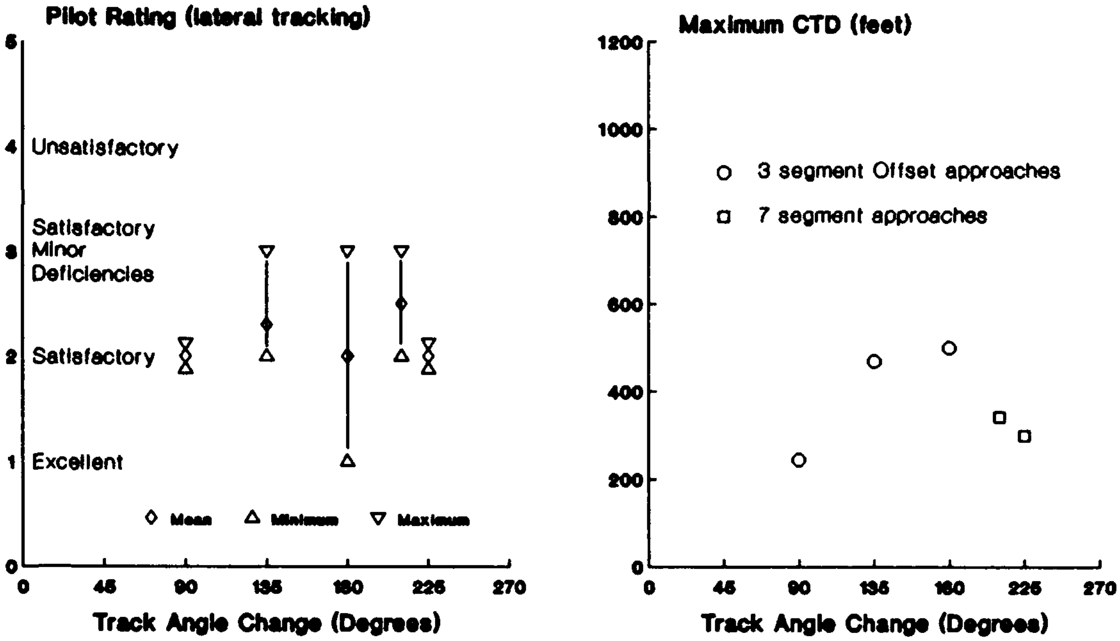

Figure 13
Pilot Rating and Maximum CTD versus Track Angle Change

8.0 CONCLUSIONS

Twin Otter Phase II MLS testing successfully demonstrated curved precision approaches of up to seven segments and 225° track angle changes. Changes made to the aircraft integrated flight system and lateral flight director between Phase I and II tests worked well in reducing the pilot workload required to accurately fly these approaches. Evaluations performed by three test pilots gave limited but consistent data; the following specific conclusions are based on these evaluations:

a. Curved approaches could be flown very accurately in light wind conditions, with the only minor problem being the mechanization of the rollout anticipation cuing;

b. In moderate to strong wind conditions, the relative changes in the wind direction experienced during a curved approach significantly affected the performance of the lateral flight director;

c. The effect of strong winds on the lateral flight director was less for approaches with several short curved segments than for approaches with longer curved segments;

d. With the enhanced lateral flight director, the accuracy of the rollout onto the final straight segment was essentially independent of the magnitude of the track angle change of the previous curved segment;

e. Glideslope interception during a curved segment was acceptable to the pilots, as long as lateral segment tracking was well established prior to intercept;

f. With the enhanced lateral flight director, the pilots rated the workload in flying the approaches as satisfactory regardless of the magnitude of the track angle changes.

Additional research would be beneficial in the areas of curved approach design and lateral flight director optimization; the IAR Twin Otter remains an excellent testbed for this type of work.

9.0 ACKNOWLEDGEMENTS:

The author would like to recognise the contributions of Messrs. J. Aitken. S. Kereliuk, and M. Morgan, the IAR test pilots who performed the evaluations, and the dedication of Mr. Chuck Taylor, who modified and maintained the inflight computing systems essential to the project. This phase of the MLS development program was partially funded by the Transport Canada MLS Project Office.

10.0 REFERENCES:

1. Erkelens L.J.J. Flight Simulations on MLS Guided Interception Procedures and Curved Approach Path Parameters, NLR MP 88035 U, National Aerospace Laboratory, Amsterdam, The Netherlands, May 1988.

2. Branstetter J.R., White W.F. B-737 Flight Test of Curved-Path and Steep-Angle Approaches Using MLS Guidance, NASA TM 101521, Langley Research Center, Hampton, Virginia, April 1989.

3. Croll J.B. Flight Evaluation of Complex Approaches in a Twin Otter Aircraft using a Microwave Landing System, LTR-FR-114, National Research Council of Canada, Ottawa, July 1990.

4. Minimum Operational Performance Standards for Airborne MLS Area Navigation equipment, Radio Technical Commission for Aeronautics (RTCA) DO-198, Washington, D.C., March 1988.

REPORT DOCUMENTATION PAGE / PAGE DE DOCUMENTATION DE RAPPORT

REPORT/RAPPORT	REPORT/RAPPORT
IAR-AN-73 1a	NRC No. 32149 1b

REPORT SECURITY CLASSIFICATION CLASSIFICATION DE SÉCURITÉ DE RAPPORT	DISTRIBUTION (LIMITATIONS)
Unclassified 2	Unlimited 3

TITLE/SUBTITLE/TITRE/SOUS-TITRE

4 Flight Evaluation of Curved MLS PrecisionApproaches in a Twin Otter Aircraft - Phase II

AUTHOR(S)/AUTEUR(S)

5 J.B. Cross

SERIES/SÉRIE

6 Aeronautical Note

CORPORATE AUTHOR/PERFORMING AGENCY/AUTEUR D'ENTREPRISE/AGENCE D'EXÉCUTION

7 National Research Council Canada
Institute for Aerospace Research
Flight Research Laboratory

SPONSORING AGENCY/AGENCE DE SUBVENTION

8

DATE	FILE/DOSSIER	LAB. ORDER COMMANDE DE LAB.	PAGES	FIGS./DIAGRAMMES
07-91 9	10	11	18 12a	13 12b

NOTES

13

DESCRIPTORS (KEY WORDS)/MOTS-CLÉS

14
1. Microwave Landing Systems
2. Twin Otter Aircraft
3. Approach Control

SUMMARY/SOMMAIRE

Phase II flight testing of curved, segmented approaches using a Microwave Langing System (MLS) was conducted on a Twin Otter aircraft belonging to the Canadian National Research Council's Institute for Aerospace Research (IAR). Precision guidance algorithms were developed for approaches with track angle changes exceeding 180°. Software development flights focussed on validating these algorithms and enhancing the existing electromechanical flight director to ease the pilot workload in tracking the curved segments. A limited number of pilot evaluations confirmed that with an enhanced lateral flight director, these approaches could be flown satisfactorily regardless of the magnitude of the track angle changes. Observations were made on approach design and wind effects on curved segment tracking.

15